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PART I

PHENOMENOLOGY

Chapter 1

INTRODUCTION

[redacted] PURPOSE [redacted]

[redacted] This manual presents a summary of the capabilities of nuclear weapons. Quantitative treatments are presented graphically in most cases. The manual is divided into two parts. Part I. Phenomenology, treats the basic phenomena of blast and shock, thermal radiation, X-ray radiation, nuclear radiation, transient radiation effects on electronics, electromagnetic pulse phenomena, and phenomena affecting electromagnetic propagation. Part II, Damage Criteria, discusses the mechanisms of casualty production and damage to military targets, and describes the response of these targets by correlating the basic physical phenomena with various defined degrees of damage.*

[redacted] The data presented here are interpretations of complex results of the nuclear weapons effects research and test programs of the Department of Defense. A constant effort is made to deduce theoretical models and scaling laws for the various weapons effects that permit a quantitative prediction of the extent of a given effect from a weapon of one yield related to weapons of other yields. Since the initiation of the limited nuclear test ban treaty, a large amount of effort has been devoted to the development of complex computer codes to predict the environments created by the various phenomena resulting from nuclear explosions and the interactions of these environments with personnel and military systems. A large number of the scaling laws presented herein were derived from the results of calculations performed with these codes.

[redacted] An estimate of the degree of reliability accompanies most of the data presented herein. Statements of the reliability of damage data only pertain to the basic effects data, which, for the target analyst represent the "radius of effect." They should not be confused with the terms variability and probability of damage, which pertain to target response; nor do these estimates include operational considerations such as linear, circular, or spherical aiming and fuzing errors, yield variations, and target intelligence.

[redacted] CHARACTERISTICS OF NUCLEAR EXPLOSIONS [redacted]

[redacted] An explosion, in general, results from the very rapid release of a large amount of energy within a limited space. This is true for a conventional "high explosive," such as TNT, as well as for a nuclear explosion. The sudden liberation of energy causes a considerable increase of temperature and pressure, so that all the materials present are converted into hot compressed gases. Detonation of high explosives results from chemical reactions, and the energy manifests primarily as blast energy, regardless of environmental conditions. For a given amount

*[redacted] The unclassified publication "The Effects of Nuclear Weapons," which contains a more detailed qualitative discussion of these basic phenomena, supplements this manual.

[redacted]

[redacted] of energy, the mass of a nuclear explosive would be much less than that of a conventional high explosive. Consequently, there is a much smaller amount of material in the weapon itself to be converted into the hot, compressed gases mentioned above in the former than in the latter case. Also, the temperatures reached in a nuclear explosion are much higher than in a conventional explosion. In a nuclear explosion the energy manifests itself in the form of blast, thermal radiation, nuclear radiation, and other electromagnetic phenomena that will be discussed in succeeding paragraphs. The energy released from a nuclear explosion is released essentially from a point source, whereas a comparable amount of energy released from a detonation of high explosives would require an enormous volume of explosive. Additionally, the energy released in a nuclear explosion results from a fission process, a fusion process, or a combination of the two, each of which involve the formation of different atomic nuclei and the release of large quantities of energy for each reaction. As mentioned previously, the energy derived from the detonation of high explosives arises from chemical reactions; these involve the rearrangement among the atoms, e.g., of hydrogen, carbon, oxygen, and nitrogen present in the high explosive material. The forces between the protons and neutrons within atomic nuclei are tremendously greater than those between atoms; consequently, nuclear energy is of a much higher order of magnitude than conventional (or chemical) energy when equal masses are considered.

1-1 Fission Energy and the Chain Reaction [redacted]

[redacted] The materials used to produce nuclear explosions by fission are certain isotopes of uranium and plutonium. Natural uranium consists mainly of two isotopes, uranium-235 (about 0.7 percent), and uranium-238 (about 99.3 percent). Uranium-235 is the much less abundant of these isotopes, but is the readily fissionable species that is commonly used in nuclear weapons. Another isotope, uranium-233, does not occur naturally, but it is readily fissionable and it can be made artificially starting with thorium-232. Since the element plutonium has no natural isotopes, the fissionable isotope used in nuclear weapons, plutonium-239, is made artificially from uranium-238.

[redacted] When a free (or unattached) neutron enters the nucleus of a fissionable atom, it can cause the nucleus to split into two smaller parts. This is the fission process, which is accompanied by the release of a large amount of energy. The smaller (or lighter) nuclei which result are called the "fission products." The complete fission of 1 pound of uranium or of plutonium releases as much explosive energy as does the explosion of about 8,000 (short) tons of TNT.

[redacted] The significant point about the fission of a uranium (or plutonium) nucleus by means of a neutron, in addition to the release of a large quantity of energy, is that the process is accompanied by the instantaneous emission of two or more neutrons; thus,

$$\text{Neutron} + \left\{\begin{array}{l}\text{uranium-235}\\ \text{(or uranium-233)}\\ \text{(or plutonium-239)}\end{array}\right\} \rightarrow \begin{array}{l}\text{fission fragments +}\\ \text{2 or 3 neutrons +}\\ \text{energy.}\end{array}$$

The neutrons liberated in this manner are able to induce fission of additional uranium (or plutonium) nuclei, each such process resulting in the emission of more neutrons which can produce further fission, and so on. Thus, in principle, a single neutron could start off a chain of nuclear fissions, the number of nuclei involved, and the energy liberated, increasing at a tremendous rate.

[redacted] There are many different ways in which the nuclei of a given fissionable species can split up into two fission fragments, but the total amount of energy liberated per fission does not vary greatly. A satisfactory average value of this energy is 200 million electron volts. The million

[redacted] electron volt (or 1 MeV) unit has been found convenient for expressing the energy released in nuclear reactions; it is equivalent to 1.6×10^{-6} erg or 1.6×10^{-13} joule. The manner in which this energy is distributed among the fission fragments and the various radiations associated with fission is shown in Table 1-1.

Table 1-1. [redacted] Distribution of Fission Energy [redacted]

	MeV
Kinetic energy of fission fragments	165 ± 5
Instantaneous gamma-ray energy	7 ± 1
Kinetic energy of fission neutrons	5 ± 0.5
Beta particles from fission products	7 ± 1
Gamma rays from fission products	6 ± 1
Neutrinos from fission products	10
Total energy per fission	200 ± 8.5

[redacted] The results in the table may be taken as being applicable to either uranium-233, uranium-235, or plutonium-239. These are the only three known substances, which are reasonably stable so that they can be stored without appreciable decay, that are capable of undergoing fission by neutrons of all energies. Hence, they are the only materials that can be used to sustain a fission chain. Uranium-238, the most abundant isotope in natural uranium, and thorium-232 will suffer fission by neutrons of high energy only, but not by those of lower energy. For this reason these substances cannot sustain a chain reaction. However, when fission does occur in these elements, the energy distribution is quite similar to that shown in the table.

[redacted] Only part of the fission energy is immediately available in a nuclear explosion; this includes the kinetic energy of the fission fragments, most of the energy of the instantaneous gamma rays, which is converted into other forms of energy within the exploding weapon, and also most of the neutron kinetic energy, but only a small fraction of the decay energy of the fission products. There is some compensation from energy released in reactions in which neutrons are captured by the weapon debris, and so it is usually accepted that about 180 MeV of energy are available per fission. There are 6.02×10^{23} nuclei in 235 grams of uranium-235 (or 239 grams of plutonium-239), and by making use of familiar conversion factors (Appendix B) the results quoted in Table 1-2 may be obtained for the energy (and other) equivalents of 1 kiloton of TNT. The calculations are based on an accepted, although somewhat arbitrary, figure of 10^{12} calories as the energy released in the explosion of this amount of TNT.*

Table 1-2. [redacted] Equivalents of 1 Kiloton of TNT [redacted]

Complete fission of 0.057 kg (57 grams or 2 ounces) fissionable material
Fission of 1.45×10^{23} nuclei
10^{12} calories
2.6×10^{25} million electron volts
4.18×10^{19} ergs
1.16×10^{6} kilowatt-hours
3.97×10^{9} British thermal units

*[redacted] The majority of the experimental and theoretical values of the explosive energy released by TNT range from 900 to 1,100 calories per gram. At one time, there was some uncertainty as to whether the term "kiloton" of TNT referred to a short kiloton (2×10^{6} pounds), a metric kiloton (2.205×10^{6} pounds), or a long kiloton (2.24×10^{6} pounds). In order to avoid ambiguity, it was agreed that the term "kiloton" would refer to the release of 10^{12} calories of explosive energy. This is equivalent to 1 short kiloton of TNT if the energy release is 1,102 calories per gram.

[redacted]

1-2 Fusion (Thermonuclear) Reactions [redacted]

[redacted] In nuclear fusion, a pair of light nuclei unite (or fuse) together, to form a nucleus of a heavier atom. An example is the fusion of the hydrogen isotope known as deuterium or "heavy hydrogen." Under suitable conditions, two deuterium nuclei may combine to form the nucleus of a heavier element, helium, with the release of energy.

[redacted] Nuclear fusion reactions can be brought about by means of very high temperatures, and they are then referred to as "thermonuclear processes." The actual quantity of energy liberated, for a given mass of material, depends on the particular isotope (or isotopes) involved in the nuclear fusion reaction. As an example, the fusion of all the nuclei present in 1 pound of the hydrogen isotope deuterium would release roughly the same amount of energy as the explosion of 26,000 tons of TNT.

[redacted] Energy production in the sun and stars is undoubtedly due to fusion reactions involving the nuclei of various light (low atomic weight) atoms. From experiments made in laboratories with charged-particle accelerators, it was concluded that the fusion of isotopes of hydrogen was possible. This element is known to exist in three isotopic forms, in which the nuclei have mass numbers of 1, 2, and 3, respectively. These are generally referred to as hydrogen (^1H), deuterium (^2H or ^2D), and tritium (^3H or ^3T). All the nuclei carry a single positive charge, i.e., they all contain one proton, but they differ in the number of neutrons. The lightest (^1H) nuclei (or protons) contain no neutrons; the deuterium (^2H) nuclei contain one neutron, and tritium (^3H) nuclei contain two neutrons.

[redacted] Several different fusion reactions have been observed between the nuclei of the three hydrogen isotopes, involving either two similar or two different nuclei. In order to make these reactions occur to an appreciable extent, the nuclei must have high energies. One way in which this energy can be supplied is by means of an accelerator, such as a cyclotron. Another possibility is to raise the temperature to very high levels. In this last circumstance the fusion processes are referred to as "thermonuclear reactions," as mentioned previously.

[redacted] Five thermonuclear fusion reactions appear to be of interest for the production of energy because they are expected to occur sufficiently rapidly at realizable temperatures; these are

$$^2D + {}^2D = {}^3He + n + 3.3 \text{ MeV}$$
$$^2D + {}^2D = {}^3T + {}^1H + 4.0 \text{ MeV}$$
$$^3T + {}^2D = {}^4He + n + 17.6 \text{ MeV}$$
$$^3T + {}^3T = {}^4He + 2n + 11.3 \text{ MeV}$$
$$^2D + {}^3He = {}^4He + {}^1H + 18.3 \text{ MeV},$$

where He is the symbol for helium and n (mass = 1) represents a neutron. The energy liberated in each case is given in million electron volt (MeV) units. The first two of these reactions occur with almost equal probability at the temperatures associated with nuclear explosions (several tens of million degrees Kelvin), whereas the third reaction has a much higher probability and the fourth and fifth a much lower probability. Thus, a valid comparison of the energy released in fusion reactions with that produced in fission can be made by noting that, as a result of the first three reactions given above, five deuterium nuclei, with a total mass of 10 units, will liberate 24.8 MeV upon fusion. On the other hand, in the fission process, e.g., of uranium-235, a mass of 235 units will produce a total of about 200 MeV of energy (paragraph 1-1). Weight for weight, therefore, the fusion of deuterium nuclei would produce nearly three times as much energy as the fission of uranium or plutonium.

[redacted] In order to make the nuclear fusion reactions take place at an appreciable rate, tempera-

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[redacted]

tures of the order of several tens of million degrees are necessary. The only practical way at present in which such temperatures can be obtained on earth is by means of a fission explosion. Consequently, by combining a quantity of deuterium (or a mixture of deuterium and tritium) with a fission device, it should be possible to initiate one or more of the thermonuclear fusion reactions given above. If these reactions accompanied by energy evolution, can be propagated rapidly through a volume of the hydrogen isotope (or isotopes) a thermonuclear explosion may be realized.

[redacted] Another reaction of interest in thermonuclear weapons is

$$^{6}Li + n \rightarrow {}^{4}He + {}^{3}T + 4.8 \text{ MeV},$$

where ^{6}Li is the symbol for the lithium-6 isotope, which makes up about 7.4 percent of natural lithium. Other reactions can occur between both lithium-6 and the more abundant isotope lithium-7 and various particles that are present within the weapon. However, the reaction shown above is of most interest for two reasons: (1) it has a high probability of occurrence; (2) if the lithium is placed in the weapon in the form of lithium-deuteride, the tritium that results from the reaction has a high probability of reacting with the deuterium to produce large amounts of energy as well as additional neutrons (see the third of the previously listed fusion reactions).

[redacted] As discussed above, several of the fusion processes between nuclei of hydrogen isotopes produce high energy neutrons. These can cause fission in uranium-238, the most abundant isotope in natural uranium, as well as in uranium-235 and plutonium-239. Consequently, association of the appropriate fusion reactions with fissile materials can result in an extensive utilization of the latter for the release of energy.

[redacted] Fission weapon yield also may be enhanced by a process known as boosting. In this process thermonuclear reactions are used to produce fast neutrons. While some energy gain is realized as a result of the thermonuclear reactions that occur, the primary increase in the yield is due to the additional fissions produced by the interaction of the fast neutrons with the fissionable materials.

1-3 Weapon Yield Ratings [redacted]

[redacted] The "yield" of a nuclear weapon is a measure of the amount of explosive energy it can produce. It is the usual practice to state the yield in terms of the quantity of TNT that would generate the same amount of energy when it explodes. Thus, a 1-kiloton nuclear weapon is one which produces the same amount of energy in an explosion as does 1 kiloton (or 1,000 tons) of TNT. As discussed in paragraph 1-1, this quantity of energy has been somewhat arbitrarily established at 10^{12} calories (see footnote on page 1-3). Similarly, a 1-megaton weapon would have the energy equivalent of 1 million tons (1,000 kilotons) of TNT, or 10^{15} calories. Since about 10 percent of the total fission energy is released in the form of residual nuclear radiation some time after the detonation (Table 1-1), this is not included when the energy yield of a nuclear explosion is stated, e.g., in terms of a TNT equivalent. Hence, in a pure fission weapon the explosion energy is about 90 percent of the total fission energy. In a thermonuclear device, the explosion energy is less than the total energy by about 10 percent of the fission contribution, e.g., if the total energy is equally divided between the fission and fusion processes, the explosion energy would be about 95 percent of the total energy of the fission and fusion reactions. This common convention will be adhered to in subsequent chapters. For example, when the yield of a nuclear weapon is quoted or used in equations, figures, etc., it will represent that por-

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[redacted]

[redacted] tion of the energy delivered within a minute or so, and will exclude the contribution of the residual nuclear radiation.

[redacted] Another method used in comparing nuclear explosion yields with conventional explosives, and one that is often confused with the rating of energy in terms of TNT energy equivalents, is the rating of effects in terms of TNT effects equivalence, i.e., the effect of a particular phenomenon of a nuclear detonation expressed in terms of the amount of TNT that would produce the same effect. An example of TNT effect equivalence is the expression of the crater radius of a nuclear surface burst in terms of the amount of TNT that would be required to produce the same radius.

[redacted] A "nominal" weapon is one whose yield is 20 kt. The use of this term arose from the approximately 20-kt yields at Hiroshima, Nagasaki, and the Bikini (Crossroads) tests. In some reports nuclear weapons effects data are based on the nominal weapon.

[redacted] For simplicity and convenience, most physical phenomena data and much of the damage data are presented as a function of the range from a 1-kt explosion, from which the phenomena or damage for other yields may be obtained readily, by the appropriate scaling procedures given wherever their use is required.

1-4 Effects of Environment and Time [redacted]

[redacted] The effects of nuclear weapons of a particular design and yield are determined by the environment in which the weapon is burst, and the time frame under consideration. The initial physical phenomena from nuclear detonations are grossly the same during the first microsecond after initiation. Several minutes after detonation, the remaining effects will be only those of residual radiation, e.g., fallout, atmospheric ionization and associated phenomena. Since the density, composition, physical state, and pressure of the medium surrounding the detonation primarily determine the resulting effects after the first microsecond, an early time history of a nuclear detonation is given in the following paragraph. This description is carried to the point when the energy released in the explosion begins to interact with its environment. Succeeding paragraphs provide brief descriptions of the phenomena that occur in different burst regimes. More complete descriptions of each phenomenon are provided in Chapters 2 through 8.

1-5 Early Time History [redacted]

[redacted] When a nuclear weapon is detonated, the actual duration of the process varies considerably, depending on the design of the weapon. It is sufficient, however, to assume that the energy is released during the first microsecond. In this period all prompt nuclear radiation (neutrons, gammas, and X-rays) has been emitted and has departed from the immediate environment of the weapon disintegration, leaving behind the energetic reaction and weapon products. These products are at high temperatures and behave as an efficient thermal radiator (see Sections I and II, Chapter 4). Although reaction products from fission will continue to decay radioactively and will emit additional gamma radiation and beta particles, they are considered as secondary effects in this time frame.

[redacted] The high temperature results in tremendous internal pressures. Under the influence of these pressures, the hot debris expands at a very high velocity. Because it is radiating energy rapidly and is being cooled by expansion, the residual weapon debris cools rapidly. Within about the first microsecond for most weapons, 70 to 80 percent of the explosion energy is emitted as thermal energy, most of which consists of X-rays. At the end of this period, most of the remaining weapon energy is kinetic energy. At this time, when all important detonation processes have taken place, the weapon debris has begun to react with its environment.

[redacted]

[redacted] AIR BURST [redacted]

[redacted] An air burst is defined as the explosion of a nuclear weapon at such a height that the weapon phenomenon of interest is not significantly modified by the earth's surface. (Also see description of high altitude burst in paragraph 1-26 to 1-29.) For example, when considering blast this height is such that the reflected wave passing through the fireball does not overtake the incident wave above the fireball (heights greater than about 160 $W^{0.35}$ ft ± 15 percent, where W is the weapon yield in kilotons). For thermal radiation, an air burst occurs at such heights above the surface that the apparent thermal yield viewed from the ground is not affected by surface phenomena, such as heat transfer to the surface, distortion of the fireball by the reflected shock wave, thermal reflection from the surface (heights above the surface greater than about 180 $W^{0.4}$ ft ± 20 percent for yields of 10 kt to 100 kt, and ± 30 percent for other yields). When considering fallout, an air burst occurs at such heights that militarily significant local fallout does not result (a minimum height of burst has generally been set at 100 $W^{0.35}$ feet, but for yields above 100 kt, 180 $W^{0.35}$ feet is recommended for a conservative estimate). For certain other phenomena of interest, e.g., neutron-induced activity, the height of burst at which the earth's surface fails to produce an effect is difficult or impossible to distinguish.

1-6 Development [redacted]

[redacted] The first interaction between weapon output and the surrounding atmosphere comes from the initial gamma rays emitted during the weapon detonation. These initial gammas arise both from the fission gammas and from gammas produced by inelastic neutron scattering in the weapon mass. These gamma rays interact mainly by Compton collisions with the electrons of the air molecules, resulting in ionization of the air and degradation of the gamma ray energy. The results of such interactions are described in Chapters 5 through 8.

[redacted] Another important interaction between the weapon output and the atmosphere comes from the neutrons produced during the fission and fusion reactions. Inelastic scattering of high-energy neutrons by nuclei of the air and the ground, and capture of slow neutrons by nitrogen in the air and by various elements in the ground provide sources of secondary gamma rays. The relative importance of the inelastic and capture gamma rays depends strongly upon the neutron spectrum of the source.

[redacted] As a result of X-ray and debris interactions, a very hot plasma remains in the vicinity of the explosion. This plasma consists of electrons and stripped nuclei of the fission and fusion products, of the elements of the weapon case and components, and of any other elements in the immediate vicinity, such as nitrogen and oxygen in the air. The radiating temperature depends on the weapon design and the total yield, but it may range from a few million to many tens of millions of degrees Kelvi[redacted] see Introduction and Section 1, Chapter 4). Although the spectrum of the emissions from this plasma is not exactly that of a black body, particularly because the temperature is by no means uniform, it often does approximate a black body spectrum [redacted] see Section 1, Chapter 4). Plasmas at these temperatures emit electromagnetic radiation that is primarily in the X-ray region of the spectrum (see Introduction, Chapter 4). If the burst occurs in the lower part of the atmosphere, the radiated energy is absorbed by the air in a sphere that initially may be only a few yards larger than the weapon. Since this sphere itself is at a high temperature, it again radiates X-rays (although at a lower temperature). The process of absorption and re-radiation continues until the energy radiated by the weapon may occupy a sphere of air

[redacted] [redacted]

[redacted]

[redacted]

of several tens of yards in diameter. The emission of this additional electromagnetic radiation covers a wide range of frequencies from about 1 cycle per second through radio, infrared, and visible to the soft X-rays.

[redacted] The photon mean free paths in the hot fireball are of the order of (or longer than) the fireball diameter, and as a result the energy distribution and temperature are fairly uniform throughout the volume of hot gas. During this phase of growth, the fireball is consequently referred to as the "isothermal sphere." This name is something of a misnomer, since temperature gradients do exist, particularly near the advancing radiation front. As the fireball cools, the growth by re-radiation of energy continues at a progressively slower rate because the mean free path of the photons becomes smaller than the fireball dimensions. The decreasing velocity of the fireball front causes the pressure of the heated air behind the front to increase, and a shock wave begins to form. This is referred to as the "outer" shock wave.

[redacted] During the isothermal sphere phase, the initially hot, high-pressure mass of weapon residues begins to expand outward as a pressure relief mechanism. Within a few microseconds, the material forms a thin, high-density shell, the hydrodynamic front, moving at high velocity. When this shell reaches the hot air outside the weapon, it begins to "snowplow" air ahead of it, and thereby transfers hydrodynamic energy into the air. The air is consequently heated further, and the additional radiation from the heated air contributes to fireball growth by radiation. Within a very short time, the hydrodynamic front becomes a strong shock wave, called the "inner" shock wave, propagating away from the burst point, but still within the fireball. All the phenomena described so far occur in the first few hundred microseconds after the explosion. During this period, fireball growth is dominated by radiation transport, with hydrodynamic energy dissipation playing a relatively minor role in the interior.

[redacted] Since the transfer of energy by radiation becomes less rapid as the fireball cools, the inner shock front begins to advance faster than the radiation front and soon the two coincide. The inner shock front continues to advance more rapidly than the radiation front and moves ahead of it at the time when the temperature of the isothermal sphere has fallen to about 300,000°C (540,000°F). This phenomenon is called "hydrodynamic separation." For a 20-kiloton explosion it occurs at about 0.1 milliseconds (10^{-4} second) after the burst time when the fireball radius is roughly 40 feet. The partition of energy between blast and thermal at the time of hydrodynamic separation is determined by the relationship between photon mean free paths, fireball radius, and time after burst. The detonation conditions determine these quantities. The final character of the environment at some distance from the burst is not determined, however, until the time at which the inner shock wave overtakes the outer one that was formed at the radiation front. At low and moderate altitudes, the inner shock front appears to catch up with the outer at hydrodynamic separation. (At higher altitudes, the inner and outer fronts do not coincide at hydrodynamic separation, and the inner shock wave does not catch up until some later time, determined by the burst conditions.)

[redacted] As the (combined) shock front from a normal air burst moves ahead of the isothermal sphere it causes a tremendous compression of the ambient air and the temperature is thereby increased to an extent sufficient to render the air incandescent. The luminous shell thus formed constitutes the advancing visible fireball during this "hydrodynamic phase" of fireball growth. The fireball now consists of two concentric regions. The inner (hotter) region is the isothermal sphere of uniform temperature, and

[redacted]

[redacted] it is surrounded by a layer of luminous, shock-heated air at a somewhat lower, but still high, temperature. The surface of separation between the very hot core and the somewhat cooler outer layer is the radiation front. The development of an air burst described in these and subsequent paragraphs is shown in Figure 1-1.

1-7 Thermal Radiation [redacted]

[redacted] The relatively large amount of thermal radiation emitted by a nuclear explosion is one of its most striking characteristics. This radiant energy may amount to from one-third to one-half of the total energy released by an air burst weapon (see Chapter 3).

[redacted] During the early stages of expansion of the incandescent shock front, the emitted radiant power increases as the luminous sphere increases in size, even though expansion causes a temperature decrease, until a maximum (the first maximum) is reached. At this point, the effect of the rapid rate of decrease in temperature overrides the enhancement of radiant power resulting from the increasing area of the luminous sphere.

[redacted] Subsequently, further expansion causes a reduction in the radiant power. Eventually the shock front temperature is reduced to a point where the shock front is no longer incandescent, at which time the rate of emission of radiation from the shock front will be negligible. In effect, the shock front has become transparent, and the hotter incandescent inner core would be expected to be observable. Initially, however, the radiation emitted from the inner core is absorbed by compounds formed in the shock-heated air, and the radiant power reaches a minimum. As these compounds break down, the radiant power emitted from the inner core begins to pass through, and the inner core becomes the visible source of radiation. Thus, the radiant power increases again. This change in boundary of the observable luminous sphere from the shock front to the incandescent inner core gives rise to the term "breakaway."

[redacted] As the opacity of the shock-heated air decreases, the apparent temperature as measured from a distance approaches that of the hot gases of the inner core, and the emitted radiant power approaches a second maximum. Further expansion and radiative cooling of the hot gases, however, give rise to a slow decrease in the radiant power. This decrease is so slow, relative to the previous rise and decline, that a large percentage of the total radiant energy emitted is delivered during this period. Finally, the rate of delivery of radiant energy drops to a low value.

[redacted] The subsequent characteristics of the shock, or blast, wave are discussed in paragraph 1-8 below and Chapter 2. The effects of the thermal pulse are discussed in Chapter 3.

1-8 The Blast Wave [redacted]

[redacted] A blast wave is characterized by a sharp rise in pressure, temperature, and density at its shock front. Thus, upon the arrival of a blast wave at a given location from the burst point, the sequence of events is a sudden increase in pressure, temperature, and density, followed by a subsequent decrease in pressure, temperature, and density to values below ambient, and a more gradual return to ambient conditions with the temperatures going slightly above ambient. The overall characteristics of the blast wave are preserved over long distances from the burst point, but vary in magnitude with distance. With increase in distance, for example, the maximum pressure in the shock wave decreases, and the length of time over which the blast pressure is above ambient, the "positive phase," increases. Also, under conditions of high relative humidity (50 percent or higher), the drop in air pressure below ambient lowers the temperature sufficiently to cause condensation of atmospheric moisture to form a large cloud called the Wilson Cloud. When the air pressure again becomes nor-

[redacted]

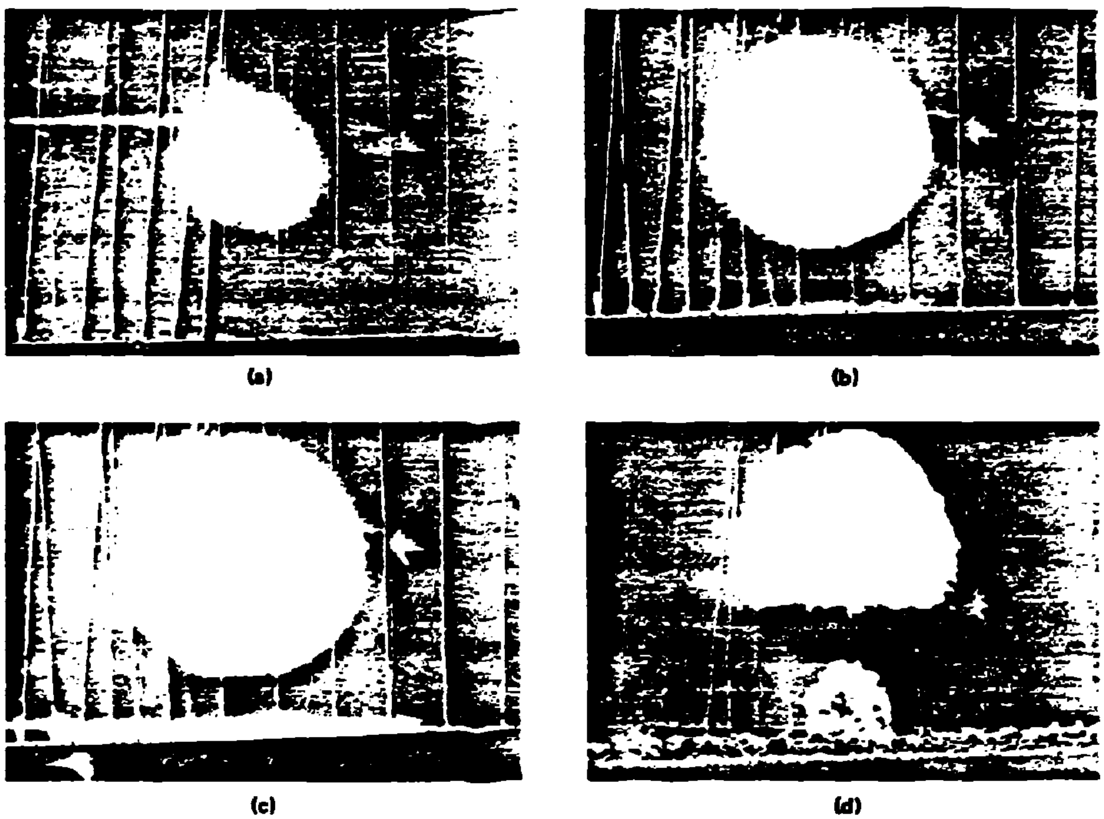


Figure 1-1. [redacted] Development of an Air Burst [redacted]

[redacted]

[redacted] mal, in a matter of seconds, the cloud disappears. Although the Wilson Cloud is spectacular, because it always occurs too far behind the shock front to modify the blast effects, and too late to reduce the thermal effects appreciably, it has no military significance.

[redacted] The motion of the air away from the burst point during the positive phase and toward the burst point during the negative phase, is also characteristic of a blast wave. The pattern of the air motion or air velocity is the same as for the other characteristics, with maximum velocity occurring just behind the shock front and decreasing with distance from the burst point. At 300 yards from the burst point of a 1-kt weapon, the peak wind velocity is about 240 miles per hour.

1-9 Nuclear Radiation [redacted]

[redacted] A unique feature of a nuclear explosion is the nuclear radiation released. This consists of, but is not limited to, gamma rays, neutrons, alpha particles, and beta particles. About a third of this energy is emitted within the first second after detonation, the remainder being released from radioactive fission products and unfissioned bomb materials over long periods of time after the burst. The effects of radiation can be increased during the first few seconds as a result of the disturbance of the atmosphere by the blast wave. Such enhancement of the effects compared to the effects in an undisturbed atmosphere is called hydrodynamic enhancement. The primary direct effect of nuclear radiation is an anti-personnel effect, with the penetrating radiations (gamma rays and neutrons) being the most dangerous. Residual nuclear radiation, due either to fallout or to neutron-induced gamma activity, can under certain conditions deny entry in a bombed area for some period of time after a detonation. Direct nuclear radiation effects on materials and equipment are of less significance, except for sensitive detector materials and certain electronic components. However, nuclear radiation produces indirect effects, such as EMP and blackout, which are discussed in Chapter 7 and 8, respectively. The nuclear radiation environment and the effects on personnel are discussed in Chapter 5. The effects of nuclear radiation on electronic components are discussed in Chapter 6.

1-10 Electromagnetic Pulse [redacted]

[redacted] The electrons that are separated from the atoms of the air by the gamma rays (paragraph 1-6) lose energy to surrounding air molecules. The energy lost in these collisions is used to free additional electrons, i.e., further ionization. The net result is a flow of negatively charged electrons radially outward from the explosion, while the heavier ions remain behind. If the explosion occurs in a homogeneous (constant density) atmosphere, two shells of charge are created: an inner positive ion shell, and an outer negative electron shell. A large local electric field is created in the radial direction; however, under such conditions, no electromagnetic field is radiated away. In practice, various asymmetries will occur that will result in electromagnetic fields being radiated from the source region. The potential importance of these fields will depend strongly on the circumstances of each individual burst. These effects are discussed in more detail in Chapter 7.

1-11 Electromagnetic Wave Propagation [redacted]

[redacted] Air burst effects on electromagnetic wave propagation are essentially associated with the fireball region. While relatively small, this region can be highly ionized for a few tens of seconds, and may have seriously degrading effects on the propagation of radio and radar signals. The effects of nuclear explosions on the propagation of electromagnetic signals are discussed in Chapter 8.

1-12 The Cloud [redacted]

[redacted] Because of its relatively low density compared to ambient conditions, the mass of hot gases making up the fireball rises. The rate of rise may reach several hundred feet per second, after which it decreases rapidly. As the gases rise, they expand, cool, and condense forming a radioactive cloud that consists largely of water vapor and metallic oxides from the weapon. As the fireball cools, the color changes gradually from red to a reddish brown, and ultimately water vapor from the air condenses sufficiently to produce a white color. As the heated mass of air in the fireball rises, cool air is pulled in from the sides and below, which may cause a doughnut-shaped ring to form around the column of hot air. This part of the cloud rolls violently as it rises. The cloud from a 1-kt detonation may reach a height of 5,000 to 10,000 ft above the burst point, after which is moves and diffuses according to the prevailing meteorological conditions.

[redacted] THE SURFACE BURST [redacted]

[redacted] A surface burst is defined as the explosion of a nuclear weapon at the earth's surface. (Figure 1-2 shows the development of a surface burst.) When a nuclear weapon is burst at the surface of the earth the sequence of events in the development of the fireball and the formation of the blast wave is the same as that for an air burst, except that the fireball boundary and the shock front are roughly hemispherical. Since the earth's surface is an almost perfect reflector for the blast wave, the resulting blast effects are almost the same as for a burst of twice the yield in free air.

1-13 Ground Shock [redacted]

[redacted] When a burst takes place on the ground surface, part of the energy is directly transmitted to the earth in the form of ground shock. Also, the air blast wave induces a ground shock wave that, at shallow depths, has essentially the same magnitude as the air blast wave at the same distance from the burst. The directly transmitted ground shock, although of higher magnitude initially, attenuates radially faster than the air blast induced shock. These effects are discussed in greater detail in Chapter 2.

1-14 The Crater [redacted]

[redacted] A land surface explosion of a nuclear weapon exerts initial shock pressures of hundreds of thousands pounds per square inch on the surface of the earth. The pressures result in displacement of material as well as downward compression of the soil to form a crater. In addition to the material that is thrown out, some earth will be vaporized by the intense heat. As will be discussed in Section II, Chapter 2, the size of the crater will depend upon the type of soil on which the explosion occurs. A crater of approximately 120 feet in diameter and 28 feet in depth is formed by a 1 kt weapon burst on a dry soil surface.

1-15 Thermal Radiation [redacted]

[redacted] As a result of the heat transfer to the surface, the hemispherical shape of the fireball, and the partial obscuration of the fireball by earth or water, the radiant exposure received by surface targets from a nuclear weapon burst on the surface is somewhat less than would be delivered by an air burst nuclear weapon of the same yield.

1-16 Initial Nuclear Radiation [redacted]

[redacted] In view of the absorption by the earth, initial nuclear radiation generally is less at the same distance from a surface burst than from an air burst; however, the hydrodynamic enhancement for high yield weapons may result in an increase in the initial gamma radiation. Each case should be examined separately by the methods described in Chapter 5 to determine the total initial nuclear radiation dose for a given situation.

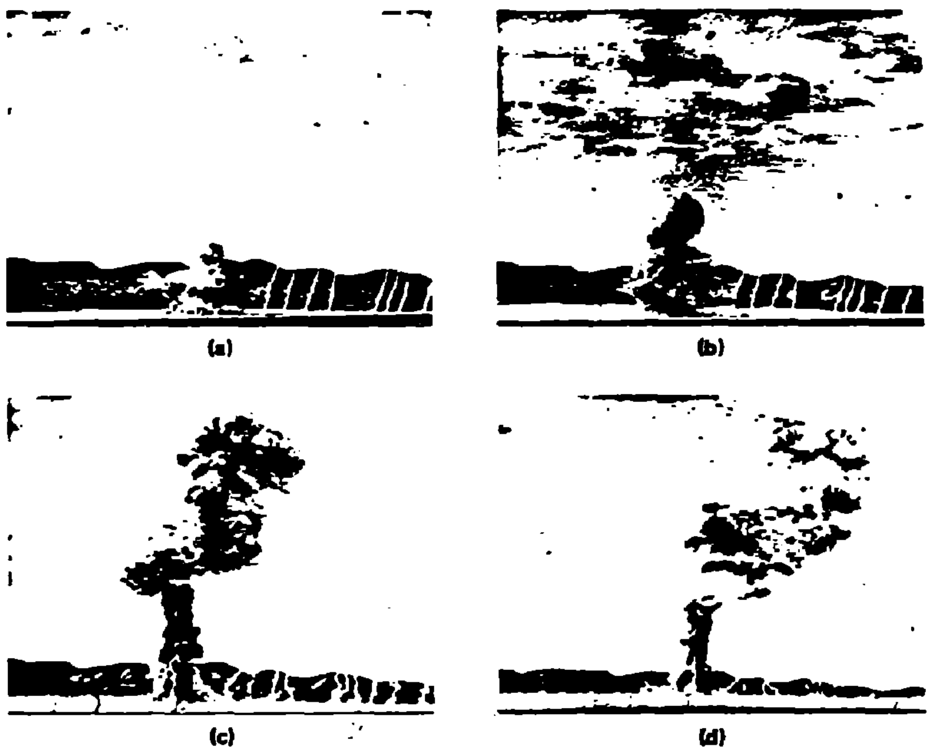


Figure 1-2. [redacted] Development of a Surface Burst [redacted]

[redacted]

1-17 Residual Nuclear Radiation [redacted]

[redacted] The contamination effects of residual nuclear radiation from a surface burst are greater than for an air burst, and hazardous radiological effects are produced over greater areas than those seriously affected by blast or by thermal radiation. Roughly half the available radioactivity resulting from a nuclear explosion on land, for example, can be expected to fall out in the general vicinity of the burst point. Dose rate contours near the burst point as great as 10,000 r/hr at H + 1 hr have been observed at tests, regardless of yield.

1-18 Electromagnetic Pulse (EMP) Radiation [redacted]

[redacted] If the detonation occurs at or near the surface of the earth, the EMP phenomenon mentioned in paragraph 1-11 produces intense electric and magnetic fields that may extend to distances of several thousand yards, depending on the weapon yield. The affected region is highly ionized and large electric currents flow in the air and the ground. Beyond this ionized region, the pulse strength drops fairly sharply, eventually as the inverse of the distance from the explosion. The strong fields may damage electrical and electronic equipment at distances exceeding those at which significant air blast damage may occur (see Chapter 7).

1-19 Electromagnetic Wave Propagation [redacted]

[redacted] Surface burst effects on electromagnetic wave propagation are essentially associated with the fireball region (see paragraph 1-11). Surface material drawn up with the fireball can cause attenuation by scattering of incident radar signals and obscuration or scintillation of optical radiation.

1-20 The Cloud [redacted]

[redacted] A great quantity of material is thrown out from the point of explosion of a nuclear weapon that bursts on the surface. As the fireball rises, some material is drawn up under the fireball, forming a stem and sometimes forming a second cloud below the one that develops from the fireball. The stem and cloud(s) continue to rise and follow the course described for air burst.

1-21 Water Surface Bursts [redacted]

[redacted] In general, the phenomena as outlined in paragraph 1-13 through 1-20 will occur for a surface burst on water. Also, the expanding sphere of hot gases depresses the water, causing the formation of a surface wave train and the transmission of a directly coupled shock wave into the water. The expanding air blast wave induces a shock wave in the water, which at shallow depths has essentially the same magnitude as the air blast wave at the same distance from the burst. Although the directly coupled water shock is of higher magnitude initially, it attenuates faster than the air blast induced water shock. As the height of burst increases from zero, depression, surface waves, and directly coupled water shock become smaller in magnitude. The formation of a crater on the bottom as the result of a surface burst in shallow water will depend on the depth of the water, yield of the weapon, and other factors. A 1 kt weapon, for example, burst on the surface of water 40 feet deep with a soft rock bottom, will form a crater 60 feet in diameter and 2 feet deep.

[redacted] THE TRANSITION ZONE BETWEEN AN AIR BURST AND A SURFACE BURST [redacted]

[redacted] There is a sizable zone above the earth's surface where, for weapons burst in the zone, the presence of the earth's surface modifies one or more of the basic weapon phenomena significantly. As the height of burst is successively lowered in this transition zone, the earth's surface plays an increasingly important role in modify-

[redacted]

[redacted]

[redacted]

ing weapon phenomena; there is a gradual transition from the characteristics of an air burst to those of a surface burst. The upper boundary of the transition zone varies depending upon the phenomenon being considered, because the effect of the earth's surface ceases to be of importance at different scaled heights of burst for different phenomena. These variations are described in detail for each phenomena in Chapters 2 through 8.

[redacted] THE HIGH-ALTITUDE BURST [redacted]

1-22 Description [redacted]

[redacted] As the detonation altitude increases, the interaction of weapon energy with the atmosphere changes markedly and is affected by weapon design and atmospheric conditions (pressure, density, and composition). There are several rather broadly defined altitude regions in which the formation and subsequent motion of the fireball differ. The term high-altitude bursts as used in this document refers to these regions collectively and includes air bursts in the lowest region.

1-23 Development [redacted]

[redacted] For detonations below about 350,000 feet, a large fraction of the X-ray energy is deposited near the burst point, heating the air to incandescence. As the detonation altitude increases above sea level, the air density decreases and the X-ray mean-free path increases. The principal mechanism for the initial fireball growth gradually changes from hydrodynamic motion (shock heating) to radiation heating. After the fireball reaches the initial size where growth by the heating of surrounding air ceases, it expands and rises in a manner related to the atmospheric scale height. The atmospheric scale height is the altitude separation where the density (or pressure) differs by a factor of e (2.7); the scale height varies from 15,000 to 25,000 feet below an altitude of 350,000 feet.

[redacted] If the initial fireball radius is smaller than the atmospheric scale height, the fireball expands to pressure equilibrium with the atmosphere. The subsequent fireball motion is similar to that described for air bursts; that is, the fireball rises principally due to buoyant forces. For yield-altitude combinations where the initial fireball radius is comparable to or exceeds an atmospheric scale height, large vertical pressure gradients are produced that cause an upward force on the fireball, giving it a boost or ballistic impulse upward. The fireball can be carried to altitudes far above the detonation point before expanding to pressure equilibrium with the surrounding atmosphere. As a result of the rapid decrease in atmospheric density with increasing altitude, the fireball density may become greater than the surrounding atmosphere. After reaching maximum altitude, the fireball then falls ballistically until encountering air of comparable density. This late-time fireball behavior will be modified if the fireball density at the maximum altitude is low enough that the ionized component of the fireball gas is trapped by the geomagnetic field.

[redacted] For detonations below about 200,000 feet, the fireball region forms a toroid. The time required appears to depend on weapon yield and detonation altitude.

[redacted] For low-altitude bursts, large temperature and pressure gradients at the boundary of the radiation fireball produce a strong shock wave (see paragraph 1-6). As the detonation altitude increases and the radiation (X-ray) fireball becomes large, the gradients at the boundary become weaker; the principal shock wave is then produced by the initial radial expansion of the debris within the X-ray fireball.

[redacted] The fireball starts as a highly ionized plasma. As it expands, it pushes the geomagnetic field out ahead of it. For detonations above about 250,000 feet, the magnetic pressure caused by the deformation of the field eventual-

[redacted]

[redacted] ly slows the expansion across the field while the expansion along the field continues. The fireball gradually becomes cylindrical in shape. After the expansion across the magnetic field has slowed, the magnetic field reenters the fireball turbulently, causing the local ionized fireball gas to become striated along the direction of the field.

[redacted] For detonations above about 350,000 feet, X-rays have a large mean-free path, deposit their energy over a large distance, and do not produce a localized fireball. However, below about 900,000 feet a fireball can be formed by deposition of the debris kinetic energy. Hydromagnetic coupling between the debris and the ionized air around the burst point results in the deposition of most of the debris kinetic energy (roughly one-fourth of the total weapon energy) near the burst point, producing a local fireball.

[redacted] The geomagnetic field plays an increasingly important role in fireball formation as the detonation altitude increases. The hydromagnetic coupling is actually quite complex. Instabilities in the interface between the expanding debris and the magnetic field can cause jetting of debris across field lines. Debris initially directed downward is stopped by the denser air below the burst point, while upward-directed debris travels to large distances. If in being stopped by the atmosphere, the downward-directed debris heats and ionizes the air, the heated region will subsequently rise and expand. Some upward-directed ionized debris will follow geomagnetic field lines across the geomagnetic equator before being deposited in the atmosphere.

[redacted] For large-yield bursts detonated above about 350,000 feet, X-ray energy, while not producing a localized fireball, will heat the atmosphere below the burst sufficiently to cause upward motion, changing the atmospheric density and composition at higher altitudes. This phenomenon is primarily important in the analysis of sequential bursts, where changes in atmospheric properties caused by one burst affect the deposition of energy (and thus the phenomenology) of succeeding bursts.

[redacted] As the fireball rises, most of the weapon debris is carried with it. After altitude stabilization takes place, the debris continues to be dispersed by diffusion and atmospheric winds. Both expansion and horizontal displacement of the debris center occur; the specific rates depend on prevailing wind motion and eddy diffusion at the debris stabilization altitudes, but they generally increase with increasing stabilization altitude. For detonations above about 200,000 feet, where the geomagnetic field acts to confine the debris, much of the debris may be trapped above several hundred thousand feet where the air density is low and wind motion negligible. However, after a period of minutes to perhaps several hours, most of the debris will have diffused or settled down the field lines to altitudes where wind motion can spread the debris over large areas. The detailed debris distribution during the early fireball growth and rise, and within the toroid at later times, is poorly known at present; however, many electromagnetic propagation effects are dependent only on the gross debris distribution.

[redacted] The differing regions of phenomenology are illustrated in the altitude-yield map shown in Figure 1-3. Figure 1-4 shows photographs taken after BLUE GILL [redacted], TEAK [redacted] 250 kilofeet), and CHECK MATE [redacted]. The formation of a toroid, characteristic of detonations in the buoyant rise region, is illustrated in Figure 1-4a. [redacted] DNA (b)(3)

[redacted] The photograph of TEAK at 100 seconds illustrates the difficulty in defining simple geometrical boundaries for fireball and debris regions. The innermost region is mostly weapon debris and heated air; the horizontal and vertical dimensions are about 450 kilofeet and 800 kilo-

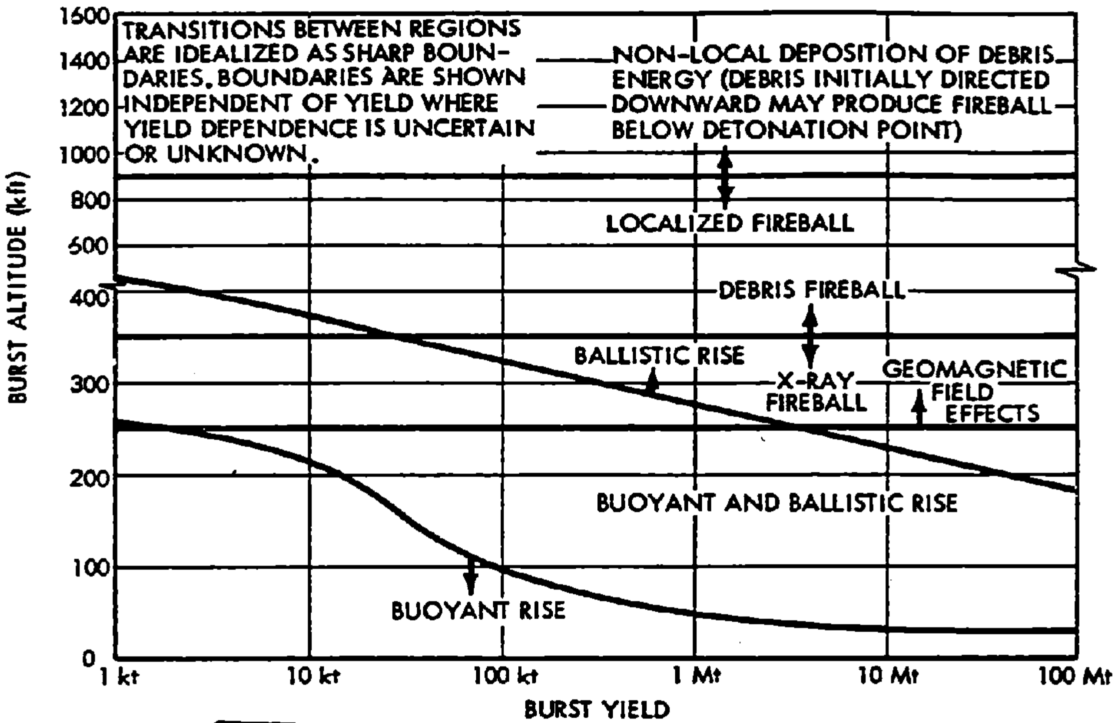


Figure 1-3. [redacted] Altitude-Yield Map Showing Differing Regions of Phenomenology [redacted]

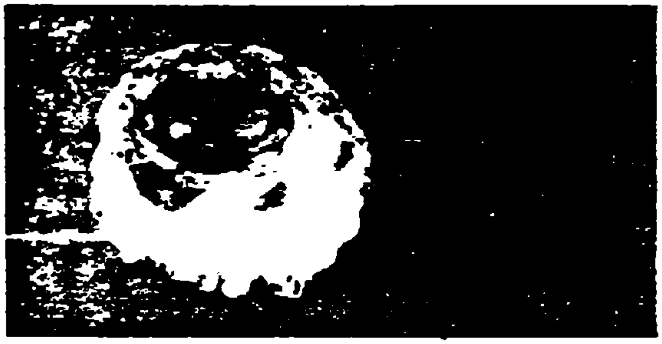
[redacted] feet. respectively. Most of the weapon debris appears to be concentrated near the bottom of the region. Some of the material near the top of the region is beginning to be affected by the geomagnetic field. The outer edge of the luminous region is a shock wave moving about 10,000 feet per second. While not defined as a fireball, there is still significant modification of the natural air chemistry within the region.

[redacted] The influence of the geomagnetic field on fireball formation and growth is clearly evident in Figure 1-4c. The overall fireball diameter is about 300 kilofeet, and the length along the geomagnetic field is about 1,000 kilofeet. The heated air within the fireball is highly ionized, with many striations oriented along the geometric field. (The dark spots within the fireball are rocket trails.)

1-24 The Blast Wave [redacted]

[redacted] As the burst height is raised, the X-rays are absorbed at longer distances from the burst as a result of their greater penetrating ability in the less dense air. The blast wave develops more slowly at higher altitudes, and at about 100,000 feet burst altitude the effective blast yield begins to decrease, until at a burst altitude of about 150,000 feet the effective blast yield is only 20 to 40 percent of what it would be at sea level for the same total energy yield.

[redacted]



(a) Blue Gill Taken From Burst Locale

(b) Teak Taken From Maui (1300 km Away)

(c) Check Mate Taken From Burst Locale

Figure 1-4. [redacted] Photographs of High Altitude Bursts, t = 100 sec [redacted]

[redacted]

[redacted]

1-25 Thermal Radiation [redacted]

[redacted] Two factors affect the thermal partition of energy at high altitudes. First, as mentioned in paragraph 1-24, shock waves form much less readily in the thinner air; consequently the fireball is able to radiate thermal energy that would, at lower altitude, have been transformed to hydrodynamic energy of the blast wave. Second, the thinner air allows energy from the nuclear source to travel much farther than is possible at sea level. Some of this energy travels so far from the source that it makes no contribution to the energy contained in the fireball. In general, the first of these factors becomes effective between about 100,000 and 140,000 feet, and the thermal efficiency rises. Above about 140,000 feet the second factor becomes more important, and the thermal efficiency drops. For burst altitudes between about 290,000 feet and 350,000 feet, a layer of incandescent air may be formed below the local fireball that was described in paragraph 1-23. This layer will be on the order of 45,000 feet thick and may be centered between about 250,000 feet and 270,000 feet, depending on the effective X-ray temperature of the weapon. This heated air will reradiate at longer wavelengths that will reach the ground and will be the primary source of thermal damage at the surface of the earth; however, the thermal radiation from the local fireball (radiation of the weapon debris and nearby air) is a potential source of eye damage, i.e., retinal burns and/or flashblindness (see Chapter 10).

1-26 Nuclear Radiation [redacted]

[redacted] Nuclear radiation also extends over large regions from high altitude bursts as a result of the thinner air. This radiation may be damaging to electronic equipment in missiles in flight (see Chapter 6 and Section VII, Chapter 9). The radiation will also produce ionization over regions large in comparison to the size of the fireball region. The extent of the ionization depends on the mean-free path of the radiation, which differs for the several nuclear radiations, and on the detonation altitude. Since the fission debris is one source for gamma rays and beta-particles, the location of the fission debris as a function of time after burst is required to determine the extent of the ionization. Energy deposition in the atmosphere from nuclear radiation also results in radiation in the optical band of the electromagnetic spectrum.

1-27 Electromagnetic Pulse [redacted]

[redacted] Detonations above about 130,000 feet produce EMP effects on the ground over areas that may encompass thousands of square miles. Although the strengths of these fields are less than half those in the highly ionized region surrounding a surface burst, they are of sufficient magnitude to damage electrical and electronic equipment. The mechanisms of formation of EMP are treated in Chapter 7.

1-28 Electromagnetic-Wave Propagation [redacted]

[redacted] A phenomenological effect of considerable interest for high detonation altitudes is persistent ionization of the atmosphere. Electromagnetic waves propagating through the ionized atmosphere can incur amplitude and phase changes, and radar and communication systems dependent on electromagnetic propagation through the atmosphere can be affected. Electromagnetic radiation emitted by the burst or by disturbed regions in the atmosphere can reduce the signal-to-noise ratio by increasing the noise background.

[redacted] For detonations below about 50,000 feet, the principal region affecting electromagnetic propagation is the fireball. While relatively small, it can be intensely ionized for a few tens of seconds. For detonations above 50,000 feet, the fireball can remain intensely ionized for tens to hundreds of seconds. A significant fraction of the primary products of the weapon can escape

[redacted]

[redacted] to great distances, and the attendant ionization (in the atmosphere) can persist for minutes to hours.

[redacted] THE UNDERGROUND BURST [redacted]

1-29 Development [redacted]

[redacted] An underground burst is defined as the explosion of a nuclear weapon in which the center of the detonation lies at any point beneath the surface of the ground. Figure 1-5 shows the development of a shallow underground burst. When a nuclear weapon is detonated at a sufficient depth underground, the ball of fire formed is composed primarily of vaporized materials from the bomb and vaporized earth. At shallow depths, light from the fireball generally may be seen from the time it breaks through the surface until it is obscured by dust and vapor clouds, a matter of a few milliseconds. The characteristics of the explosion and their related effects depend upon the depth, yield, and soil type. As the depth below the surface is increased, the characteristics depart gradually from those of a surface burst and finally, at depths of the order of 20 feet for a 1 kt detonation, the explosion exhibits the phenomena commonly associated with underground explosions. It is emphasized that the transition from the observed characteristics of a surface burst to those of an underground burst is not sudden, but that the characteristics change gradually.

1-30 Air Blast [redacted]

[redacted] Bursts at depths shallow enough to permit significant venting will produce air blast waves similar to those of air or surface bursts. As the depth of burst increases, the magnitude of the air blast will decrease.

1-31 Column, Cloud, and Base Surge [redacted]

[redacted] The first physical manifestation of an underground explosion at shallow depths is an incandescence at the ground surface directly above the point of detonation. This is almost immediately followed by large quantities of material being thrown vertically as a consequence of the direct ground shock reflection along the ground surface. Concurrently, large quantities of gas are released. These gases entrain additional quantities of material and carry them high into the air in the form of a cylindrical column. As the column rises it fans out and forms a dense cloud. Some of the particles thrown vertically, together with the entrained particles behave like an aerosol with a density considerably greater than the surrounding air. This aerosol subsequently falls in the immediate vicinity of ground zero, and the finer soil particles spread out radially along the ground to form a low dust cloud called the base surge. For a 1 kt weapon burst at a depth of 20 ft, it is estimated that the column will reach a height of approximately 420 ft and a diameter of 660 ft, the base surge will be 4,400 ft in diameter and the upper cloud will be 5,000 ft in height. Dimensions of the base surge are discussed in Section II, Chapter 2. For shallower depths of burst, the column tends to assume the shape of an inverted cone rather than a cylindrical column and has a more pronounced radial throwout. Shallower depths of burst also become less favorable for the formation of a base surge, approaching the conditions of a surface burst where no base surge is expected.

1-32 Ground Shock [redacted]

[redacted] As a burst is moved deeper and deeper into the ground, the directly transmitted ground shock increases in importance and the air induced ground shock becomes less important.

1-33 Crater [redacted]

[redacted] Formation of the crater from an underground burst is essentially the same as for a surface burst, except that at shallow depths more material is thrown vertically. Subsequently,

[redacted]

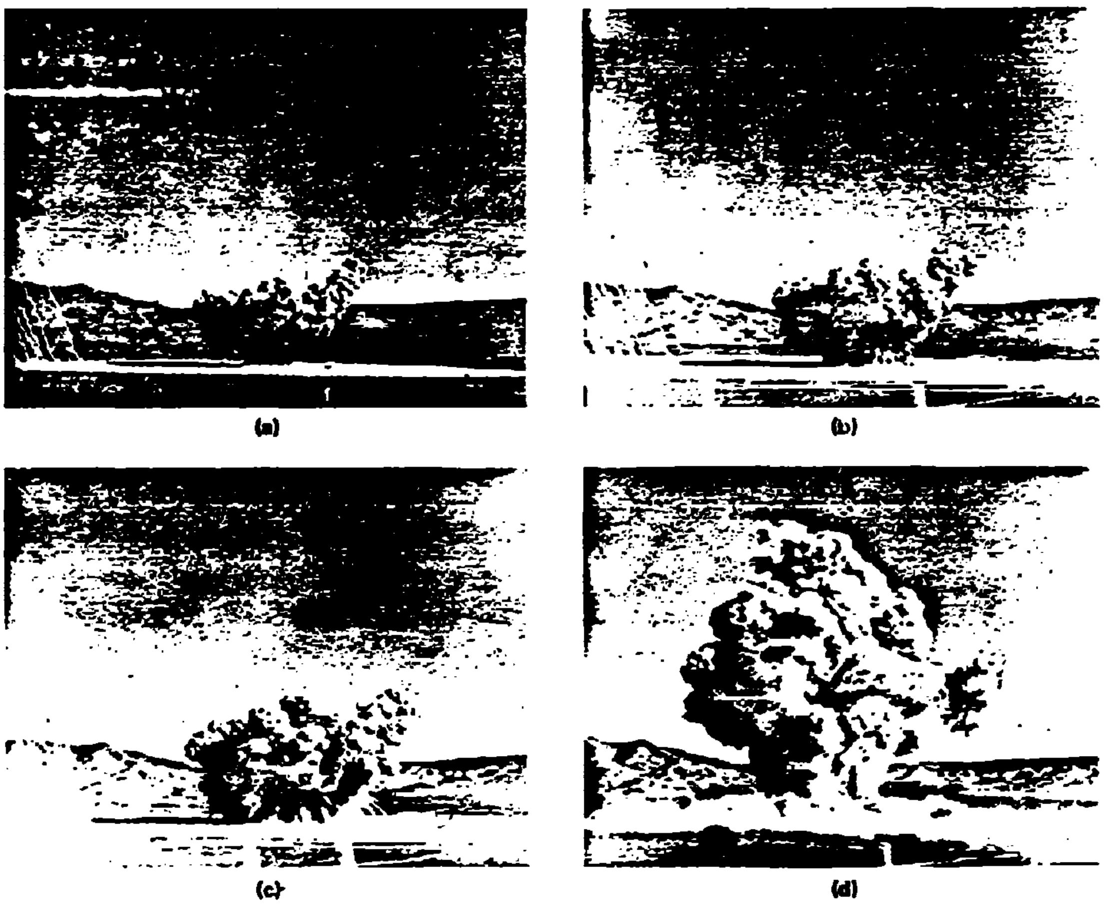
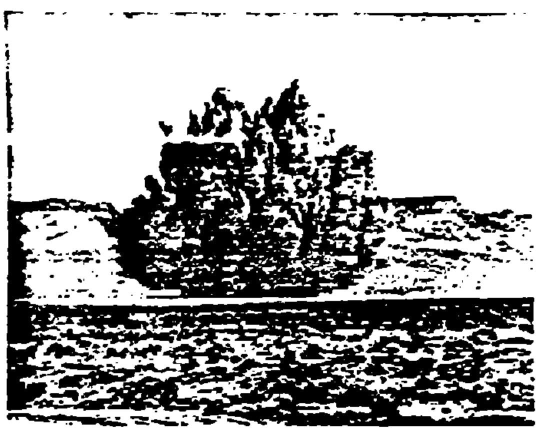


Figure 1-5. [redacted] Development of a Shallow Underground Burst [redacted]

[redacted]

[redacted]



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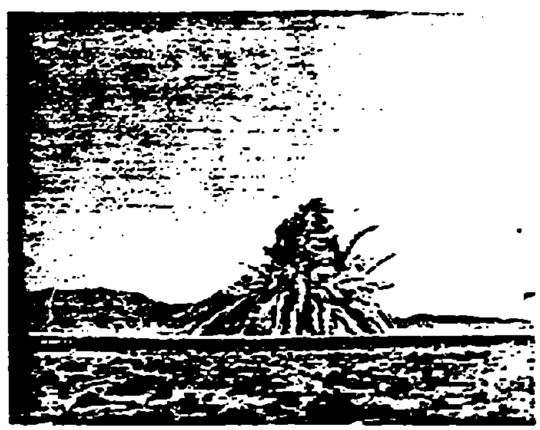

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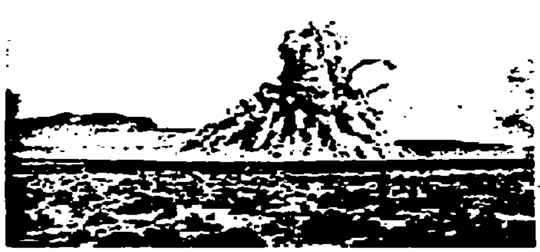

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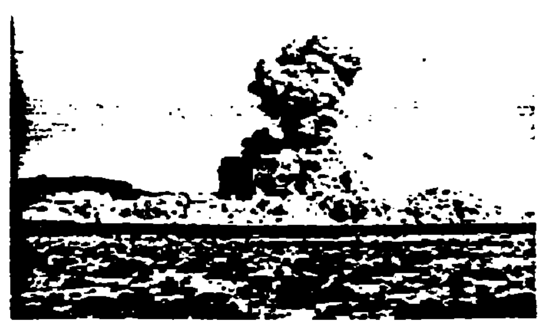


(d)

Figure 1-6. [redacted] Development of a Deep Underground Burst [redacted]

[redacted]

[redacted] much of the ejected material collapses and falls back, partly into the newly formed crater and partly onto the surrounding "lip." The general term "fallback" is used to describe the material that immediately falls back into the crater. The term "ejecta" describes material which has fallen onto the crater lip. The size of the remaining (or "apparent") crater depends on the energy yield of the detonation and on the nature of the excavated medium. In general, for equivalent conditions, the volume of the crater is roughly proportional to the yield of the explosion.

[redacted] The size of the apparent crater increases with increasing depth until a certain optimum depth is reached. The scaled optimum depth is different for the crater radius than for the crater depth and also varies markedly for different media. At depths below the optimum for the particular medium surrounding the burst, the crater dimensions decrease with increasing depth. At sufficiently deep depths the explosion will not vent to the surface and a cavity (camouflet) will be formed. There may or may not be disturbances at the surface, depending on the depth of the detonation and the material comprising the ground.

1-34 Thermal and Nuclear Radiation [redacted]

[redacted] As a general rule, the thermal radiation will be almost completely absorbed by the ground material, so that it does not represent a significant hazard. Most of the neutrons and early gamma rays will also be removed, although the capture of the neutrons may cause a considerable amount of induced radioactivity in various materials present in the soil. This will constitute a small part of the residual nuclear radiation, of importance only in the close vicinity of the point of burst. The remainder of the residual radiation will be due to the contaminated base surge and fallout. For shallow depths of burst, the fallout effects are similar to those of a surface burst. As the depth of burst increases however, more and more of the contaminant is deposited in the immediate vicinity of the detonation, until for the case of no surface venting, all of the contaminant is contained in the volume of the ruptured earth surrounding the point of detonation.

1-35 Electromagnetic Pulse [redacted]

[redacted] For shallow depth of burst, the electromagnetic pulse should be similar to, but of lesser magnitude than, that for a surface burst of the same size. As depth of burst increases, the extent and magnitude of the pulse will diminish. In general, the electromagnetic pulse from such bursts should be a much less significant damage mechanism than ground shock. Adequate test data for prediction are, however, lacking.

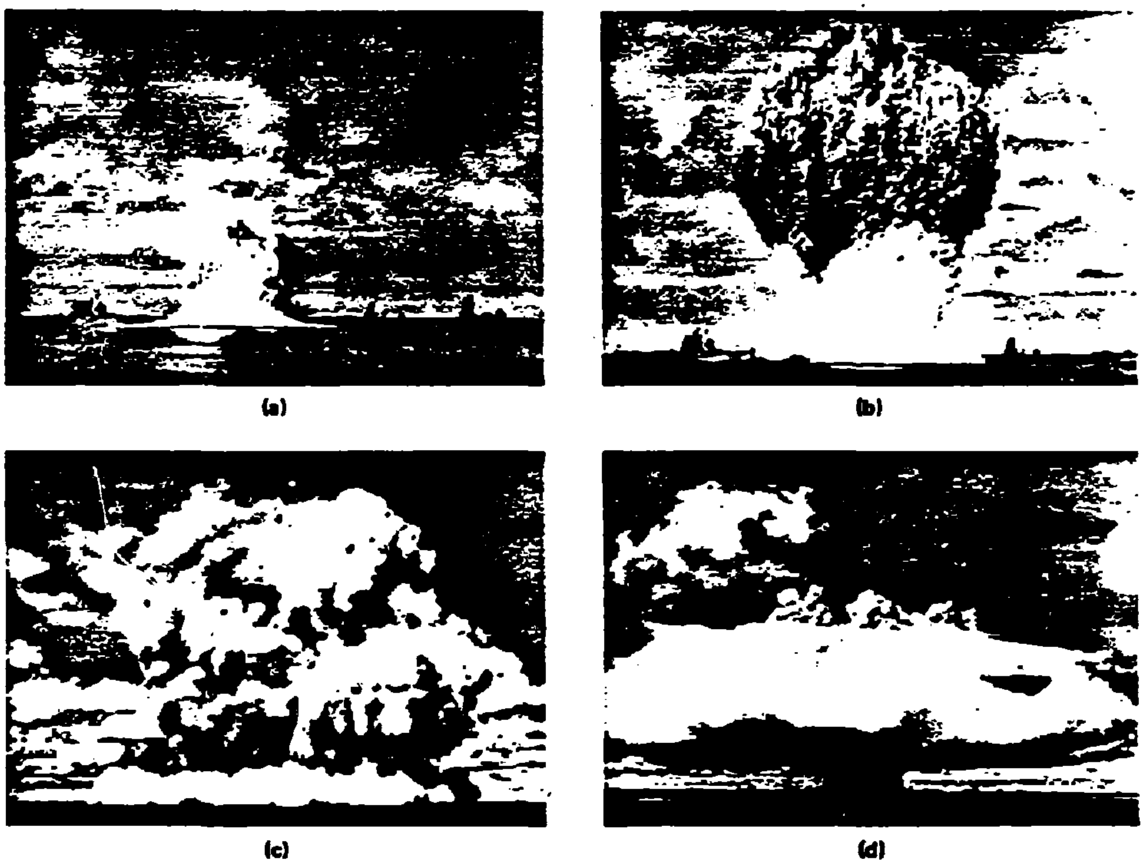
[redacted] THE UNDERWATER BURST [redacted]

1-36 Development [redacted]

[redacted] An underwater burst is defined as the explosion of a nuclear weapon in which the center of the detonation lies at any point beneath the surface of the water. (Figure 1-7 shows development of a shallow underwater burst; Figure 1-8 shows development of a deep underwater burst.) An underwater nuclear explosion releases large amounts of thermal and nuclear radiation, essentially all of which is absorbed by the surrounding water within several feet of the explosion. (Some radiation within the visible spectrum can be radiated to greater distances depending on the transparency of the water.)

[redacted] During the early stages of the explosion, the bomb materials attain a very high temperature (on the order of millions of degrees) and a very high pressure (on the order of millions of atmospheres). Energy acquired by these materials is transferred to the layer of water closest to the bomb, which is heated and compressed and which, then, heats and compresses the next

[redacted]



(a) (b) (c) (d)

Figure 1-7. [redacted] Development of a Shallow Underwater Burst [redacted]

[redacted]

(a)

(b)

(c)

(d)

Figure 1-8. [redacted] Development of a Deep Underwater Burst [redacted]

[redacted]

[redacted]

outward layer. By this mechanism, a wave of compression (the hydrodynamic or shock front) is formed and moves outward from the bomb. This front moves faster than the material it engulfs, which also moves outward but at a slower rate.

[redacted] As the shock front moves away from the point of explosion, energy is dissipated in the form of heat, which raises the temperature of the water passed over by the front. The largest temperature increase occurs near the center of the explosion, where it is great enough that the water is not only vaporized, but dissociated as well. At somewhat greater distances, the water is vaporized and turned to steam; at still greater distances, the water is heated, but not to its boiling point.

[redacted] Thus, shortly after an underwater burst, an expanding bubble is formed. This bubble is composed largely of vaporized water with radioactive debris at its center, surrounded by heated water. Continued expansion of this bubble results in a pressure reduction within it. As the bubble pressure falls below the vapor pressure of the heated water, vaporization of additional water occurs at the interface of the bubble and the water.

[redacted] In a deep underwater explosion, the bubble continues to expand at a decreasing rate until a maximum size is reached. If not too near the surface or the bottom, the bubble remains roughly spherical to this point. As a result of the inertia of the water set in motion by the early expansion of the bubble it actually overexpands, i.e., when it does attain its maximum size, its contents are at a pressure well below the ambient water pressure.

[redacted] The higher pressure around the bubble causes it to contract, with a resultant increase in internal bubble pressure, and condensation of some of the bubble contents. Because the hydrostatic pressure at the bubble bottom is larger than at the top, the bubble does not remain spherical during the contracting phase. Its bottom moves inward faster than its top (which may remain stationary or even rise slightly), contacts the top (forming a doughnut-shaped bubble viewed from above), and causes turbulence and mixing of the bubble contents with the surrounding water.

[redacted] The inertia of the water set in motion by contraction of the bubble causes it to overcontract, and its internal pressure once more becomes higher than the ambient water pressure. A second compression (shock) wave in the water commences after the bubble reaches its minimum volume. This compression wave has a lower peak overpressure but a longer duration than the initial shock wave in the water. A second cycle of bubble expansion and contraction then begins.

[redacted] During the initial expansion cycle, the bubble is relatively stationary, but upon contracting begins to migrate upward under the action of buoyant forces. The rate of upward migration is greatest at times of bubble minimum size, and is almost zero at times of maximum size, when the bubble is again almost spherical.

[redacted] If the explosion occurs far enough from the surface, the bubble continues to pulsate and rise, though after three complete cycles enough condensation of steam has taken place to make it unlikely that additional pulsations will occur. During pulsation and upward migration, however, the water in the vicinity of the bubble acquires considerable upward momentum, and eventually breaks through the surface with some violence.

[redacted] For shallow bursts, the bubble may b[redacted] through the surface during one of the early pulsations or even before completion of a single pulsation cycle. If such a breakthrough occurs during the portion of the cycle at which bubble pressure is higher than ambient pressure (as with a very shallow explosion), a phenomenon known as a blowout occurs. If breakthrough

[redacted]

[redacted]

[redacted]

occurs when bubble pressure is below ambient pressure, the reverse phenomenon, blow-in, occurs. The character of the surface effects differs for the two phenomena. (See paragraph 1-39.)

[redacted] If a burst occurs near the sea (or harbor) bottom, the general bubble behavior is as described above. A pulsating bubble, however, is drawn toward the bottom and, therefore, bubble migration toward the surface is slowed.

1-37 Water Shock Waves and Other Pressure Pulses [redacted]

[redacted] The primary shock wave that moves out from the explosion center is characterized by an extremely rapid increase in pressure (virtually instantaneous) to a very high initial or peak pressure, and then an almost exponential decrease to a value less than the hydrostatic pressure at the explosion point. Though a water shock wave resembles an air blast wave superficially, its peak pressures are generally much higher, and durations much shorter. In the absence of nearby boundaries, the shock wave proceeds outward radially at a very high initial velocity, which soon decreases to nearly the velocity of sound in water (about 5,000 ft/sec). Shock wave velocity depends on water temperature, density, and salinity; and therefore, a shock wave may be bent (refracted) as it moves through regions of differing characteristics.

[redacted] Shock wave reflections from the surface and bottom affect the shock and pressure field at a point distant from the explosion. Since reflection from the surface is in the form of a negative, or tension wave, it can cause a shortening of the pressure pulse (cutoff), and, when the shock wave encounters the surface at a small enough angle, reflection can even reduce the magnitude of the primary pressure pulse. Reflection from the bottom generates a second compression wave in the water that can be effective in damaging ships.

[redacted] Additional shock and pressure waves, generally of lesser importance than the primary shock wave or the bottom reflected shock waves, can be generated by shock wave energy that has been transmitted to bottom material or to the air and retransmitted to the water, by the collapse of a cavitation region near the surface, and by re-reflections of any of these.

[redacted] Shock or compression waves from subsequent bubble pulses generally behave in the same manner as the initial shock wave and undergo reflection and refraction of the same character.

1-38 Air Blast [redacted]

[redacted] As in the case of an underground burst, air blast waves are formed by an underwater burst. Their propagation depends upon the depth of burst. The first air blast wave from an underwater burst is that formed by the transfer of the shock front across the water-air interface. This front appears as a flat dome. The second air blast wave is transmitted by the venting bubble. This front will propagate essentially hemispherically. For shallow burst depths, the air blast wave resulting from venting is more intense than the shock wave transmitted across the water-air interface. For deep bursts, on the other hand, the shock wave transmitted across the water-air interface yields the higher pressures.

1-39 Surface Effects [redacted]

[redacted] The first surface effect of an underwater burst is caused by the intersection of the primary shock wave and the surface. Viewed from above, the effect appears to be a rapidly expanding ring of darkened water (often called the "slick"). Following closely behind the darkened region is a white circular patch (the "crack") probably caused by underwater cavitation produced by the reflected rarefaction wave. Shortly after appearance of the crack, the water above the explosion rises vertically and forms a white mound of spray (the "spray dome"). This dome

[redacted]

[redacted]

[redacted] is caused by the velocity imparted to the water near the surface by the reflection of the shock wave and to the subsequent breakup of the surface layer into drops of spray. The initial upward velocity of the water is proportional to the pressure of the direct shock wave, and so it is greatest directly above the detonation point. Consequently, the water in the center rises more rapidly (and for a longer time) than water farther away. As a result, the sides of the spray dome become steeper as the water rises. The upward motion is terminated by the downward pull of gravity and the resistance of the air. The total time of rise and the maximum height depend upon the energy of the explosion, and upon its depth below the water surface. Additional slick, crack, and spray-dome phenomena may result if the shock wave reflected from the water bottom and compression waves produced by the gas bubble reach the surface with sufficient intensity.

[redacted] For shallow bursts, the spray dome appears to be rapidly converted to a column formed by the upward and outward acceleration of the water surrounding the explosion. If blowout occurs, the upper part of the column is likely to be marked by a crown of explosion products. If blow-in occurs, the crown is likely to be absent. In its later stages, the column may break up into plumes (relatively broad jets or spouts of water that disintegrate into spray as they travel through the air).

[redacted] For bursts deep enough that blowout does not occur, but not so deep that bubble pulsation has ceased, plumes will be formed.

[redacted] If an explosion takes place deep enough for bubble pulsations to have ceased before the bubble reaches the surface, plumes caused by the upwelling of the water (and any uncondensed vapor or gas) may occur.

[redacted] Upon subsidence of the column and plumes from an underwater explosion, a misty, generally highly radioactive, "doughnut-shaped ring" or series of rings, the "base surge" may be formed. In the few instances in which base surge formation has been observed over water, the visible configuration has been quite irregular. Nevertheless, to a good approximation, the base surge can be represented as a hollow cylinder with the inner diameter about two-thirds of the outer diameter. The heights of the visible base surge clouds have generally ranged between 1,000 and 2,000 feet.

[redacted] The necessary conditions for the formation of a base surge have not been definitely established, although it is reasonably certain that no base surge would accompany bursts at great depths. The underwater test shots upon which the present analysis is based have all created both a visible and an invisible (see below) base surge. The only marked difference between the phenomena at the various tests is that at Bikini BAKER there was an airborne cloud, evidently composed of fission debris and steam. The other shots, which were at somewhat greater depths, produced no such cloud. The whole of the plume fell back into the surface of the water where the low-lying base surge cloud was formed.

[redacted] From the weapons effects standpoint, the importance of the base surge lies in the fact that it is likely to be highly radioactive because of the fission (and other) residues present either at its inception, or dropped into it from the radioactive cloud. Because of its radioactivity, it may represent a serious hazard for a distance of several miles, especially in the downwind direction. The fission debris is suspended in the form of very small particles that occupy the same volume as the visible base surge at early times, that is, within the first 3 or 4 minutes. However, when the small water droplets which make the base surge visible evaporate and disappear, the radioactive particles and gases remain in the air and continue to move outwards as an invisible radioactive base surge. There may well be some fallout or rainout on the surface of the water (or

[redacted]

[redacted]

[redacted]

ship or shore station) from the radioactive base surge, but in many cases it is expected to pass over without depositing any debris. Thus, according to circumstances, there may or may not be radioactive contamination on the surfaces of objects in the vicinity of an underwater nuclear burst.

[redacted] The radioactive base surge continues to expand in the same manner as would have been expected had it remained visible. It drifts downwind either as an invisible, doughnut-shaped cloud. or as several such possibly concentric clouds that approximate a low-lying disc with no hole in the center. The latter shape is more probable for deeper bursts. The length of time this base surge remains radioactive will depend on the energy yield of the explosion, the burst depth. and the nearness of the sea bottom to the point of burst. In addition, weather conditions will control depletion of debris due to rainout and diffusion by atmospheric winds. As a general rule, it is expected that there will be a considerable hazard from the radioactive base surge within the first 5 to 10 minutes after an underwater explosion and a decreasing hazard for half an hour or more.

[redacted] After dissipation of the visible base surge, the water surface around the explosion is seen to be white. This area (the "foam patch") results from the upward motion of the water and uncondensed explosion products in the vicinity of the bubble, their spreading over the surface of the patch, and their downward motion at the edge of the patch. In its later stages, this area is marked mainly by a ring of foam and debris that shows where downward circulation has taken place.

1-40 Thermal and Nuclear Radiation [redacted]

[redacted] Thermal radiation and initial nuclear radiation effects are considered to be insignificant for underwater bursts, except for the radioactivity accompanying the base surge (paragraph 1-39). Residual nuclear radiation effects (fallout) will approximate those of a ground surface burst if the explosion occurs in shallow water.

1-41 Electromagnetic Pulse [redacted]

[redacted] The degree to which an electromagnetic pulse is generated by an underwater burst is not known, but it is expected to be insignificant except for very shallow bursts. In such cases, it is believed that a diminishing effect above the surface, approximating that described for a shallow underground burst, will result.

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*Additional reference material concerning the subject matter of this chapter may be found in the handbooks described in Appendix D and in the more specific bibliographies of Chapters 2 through 8.

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